



The Thomas Jefferson National Accelerator Facility
Theory Group Preprint Series

Additional copies are available from the authors.

The Southeastern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract DE-AC05-84ER40150.

DISCLAIMER

This report was prepared as an account of work sponsored by the United States government. Neither the United States nor the United States Department of Energy, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Phenomenological Study of Strong Decays of Heavy Hadrons in Heavy Quark Effective Theory

N. Trégourès*

Department of Physics, Old Dominion University, Norfolk, VA 23529
and Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue
Newport News, VA 23606

and

W. Roberts†

National Science Foundation, 4201 Wilson Boulevard, Arlington, VA 22230

The application of the tensor formalism of the heavy quark effective theory (HQET) at leading order to strong decays of heavy hadrons is presented. Comparisons between experimental and theoretical predictions of ratios of decay rates for B mesons, D mesons and kaons are given. The application of HQET to strange mesons presents some encouraging results. The spin-flavor symmetry is used to predict some decay rates that have not yet been measured.

JLAB-THY-99-34

I. INTRODUCTION

In a recent article [1], the formalism of the heavy quark effective theory (HQET) [2-4] was applied to the strong decays of heavy hadrons. In that article, it was shown that the results for the ratios of decay rates obtained by Isgur and Wise [5] in their spin counting arguments, and by other authors in the combined HQET/chiral perturbation theory [6,7], were reproduced. It was also shown that the treatment of decays beyond the S - and P - wave pion emissions of heavy hadrons were relatively easy to handle.

In this article, we test the formalism by applying it to the measured decays of charmed and beauty hadrons. However, since the data in these two sectors are limited, we also examine strange hadrons, assuming that we can treat the strange quark as a heavy one. This has been done by other authors in the past, with reasonable success [8], and we find that our formalism, applied to strange hadrons, also works surprisingly well.

In the next section, we briefly review the salient points of the application of HQET to the strong decays of hadrons. In section 3 we present our results, while in section 4 we give our conclusions. Note that most of the experimental results presented in section 3 are obtained from the Particle Data Group [9], unless a specific reference is given. For the excited B mesons, data are taken from [10-13].

II. MATRIX ELEMENTS OF STRONG DECAYS

For the sake of completeness, we include here the salient points of HQET as applied to the strong decays of heavy hadrons. The decay amplitude for

$$H_Q \longrightarrow H'_Q + H_L, \quad (1)$$

where H_L is a light hadron is given by

$$\mathcal{M} = \langle H_L H'_Q | \mathcal{O}_s | H_Q \rangle, \quad (2)$$

where \mathcal{O}_s is the operator responsible for the strong decay. Unlike electroweak processes, we do not know the explicit form of \mathcal{O}_s . It is expected to be a complicated object involving non-perturbative QCD acting on composite, strongly-interacting particles. The only thing we know is that \mathcal{O}_s is a Lorentz scalar operator as well as an operator that is a

*Present address: Laboratoire de Physique et Modélisation des Milieux Condensés CNRS, Maison des Magistères, Université Joseph Fourier B.P. 166, 38042 Grenoble Cedex 9, France.

†On leave from the Department of Physics, Old Dominion University, Norfolk, VA 23529, and from Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, VA 23606

singlet in all flavors of quarks. Nevertheless we are free to parametrize \mathcal{O}_s in a way that is useful for our purposes. Since HQET helps us to deal with the heavy quark field, it is of interest to focus on the heavy quark part of \mathcal{O}_s . Without loss of generality, we parametrize \mathcal{O}_s as [1]

$$\mathcal{O}_s = \sum_i \bar{Q} \Gamma_i Q L_i, \quad (4)$$

where Q is the heavy quark field, Γ_i is one of the 16 matrices $I, \gamma_\mu, \sigma_{\mu\nu}, \gamma_\mu \gamma_5, \gamma_5$ and L_i contains all our ignorance of the dynamics of the light degrees of freedom. L_i has the same Lorentz structure as Γ_i so that \mathcal{O}_s is a Lorentz scalar operator. Only heavy quark loop terms are omitted in this parametrization of \mathcal{O}_s , but these contributions are suppressed by powers of $1/m_Q$.

In the heavy quark limit, the heavy quark does not recoil or flip its spin during the decay, thus acting as a spectator. The only possible term that contributes to the strong decay operator in this case is the term $\Gamma_i = I$ [1], i.e.,

$$\mathcal{O}_s \rightarrow \bar{h} i h L, m_Q \rightarrow \infty. \quad (4)$$

where L is an unknown scalar operator that acts on the brown muck component of the hadron, and h is the effective heavy quark field [2–4]. In the heavy quark limit the decay amplitude thus becomes

$$\mathcal{M} = \langle H_i H_Q | \bar{h} h L | H_Q \rangle. \quad (5)$$

In order to calculate \mathcal{M} , we use the representations of states developed by Falk [14]. For concreteness let us examine the example of a meson decay. Consider the decay of the meson doublet $(1^+, 2^+)$, $J_P^P = \frac{3}{2}^+$, to the meson doublet $(0^-, 1^-)$, $J_P^P = \frac{1}{2}^-$ with the emission of a single pion. The four possible decays are

$$\begin{aligned} D_1 &\rightarrow D + \pi, \\ D_1 &\rightarrow D^* + \pi, \\ D_2 &\rightarrow D + \pi, \\ D_2 &\rightarrow D^* + \pi. \end{aligned}$$

At leading order in HQET (i.e., in the limit that the mass of the heavy quark goes to infinity) the matrix elements are [1]

$$\mathcal{M}_{1D} = \langle D\pi(p) | \bar{c} c L | D_1 \rangle = \sqrt{m_D m_{D^*}} \text{Tr}[\gamma_5 T_\mu \bar{D} D_1^\mu], \quad (6)$$

$$\mathcal{M}_{1D^*} = \langle D^*\pi(p) | \bar{c} c L | D_1 \rangle = \sqrt{m_{D^*} m_{D_1}} \text{Tr}[\gamma_5 T_\mu \bar{D}^* D_1^\mu], \quad (7)$$

$$\mathcal{M}_{2D} = \langle D\pi(p) | \bar{c} c L | D_2 \rangle = \sqrt{m_D m_{D_2}} \text{Tr}[\gamma_5 T_\mu \bar{D} D_2^\mu], \quad (8)$$

$$\mathcal{M}_{2D^*} = \langle D^*\pi(p) | \bar{c} c L | D_2 \rangle = \sqrt{m_{D^*} m_{D_2}} \text{Tr}[\gamma_5 T_\mu \bar{D}^* D_2^\mu], \quad (9)$$

where D, D^*, D_1^μ and D_2^μ are the tensor representations of D, D^*, D_1 and D_2 , respectively, [14].

The only non-redundant form allowable for T_μ is [1]

$$T_\mu = \alpha p_\mu, \quad (10)$$

where p is the four momentum of the pion. The constant α parametrizes our ignorance of the non-perturbative aspects of these decays. It is a constant that may be estimated in a quark model, for instance, but it is one about which HQET can say nothing. The form written above is valid for all four decays considered. Consequently, ratios of decay rates of any of these processes are fully determined by the heavy quark formalism. Moreover, due to the flavor symmetry and our choice of normalization, the coupling constant α would be the same in the case of the b -flavored as well as s -flavored mesons (if the s quark is treated as heavy). This means that, had we used B, B^*, B_1, B_2 or K, K^*, K_1, K_2 instead of D, D^*, D_1, D_2 the expressions (6) to (9) would have been exactly the same but for the mass factors.

III. RESULTS

A. D_1 and D_2

We first apply HQET to D mesons. Using the heavy quark limit is not as reasonable as it would be for B mesons, but more data are available. The experimental status of D mesons is summarized in table I. D_1 and D_2 are believed to correspond to the doublet $(1^+, 2^+)$, $J_P^P = \frac{3}{2}^+$ while D and D^* correspond to the doublet $(0^-, 1^-)$, $J_P^P = \frac{1}{2}^-$.

J_P^P	J_P^P	State	Mass (MeV)	Γ (MeV)	Γ_{D^*} (MeV)	$\Gamma_{D^* \pi}$ (MeV)
$\frac{1}{2}^-$	0^-	D^0	1864.6 ± 0.6	$\tau = 0.415 \pm 0.004 \text{ ps}$	—	—
		D^{\pm}	1869.3 ± 0.6	$\tau = 1.057 \pm 0.015 \text{ ps}$	—	—
	1^-	D^{0*}	2066.7 ± 0.6	< 2.1	< 1.3	—
		$D^{0\pm}$	2010.0 ± 0.6	< 0.131	< 0.130	—
$\frac{3}{2}^+$	1^+	$D_1(2420)^0$	2422.2 ± 1.8	$18.0^{+4.4}_{-3.5}$	not seen	seen
		$D_1(2420)^{\pm}$	2427 ± 5	28 ± 8	not seen	seen
	2^+	$D_2(2460)^0$	2459.9 ± 2.0	23 ± 5	seen	seen
		$D_2(2460)^{\pm}$	2459 ± 4	25^{+6}_{-7}	seen	seen

TABLE I. Summary of D meson experimental status. J_P^P is the spin-parity of the light degrees of freedom according to the HQET.

Ratios of widths	Experiment	Heavy quark prediction
$\frac{\Gamma(D_1^0 \rightarrow D^+ \pi^-)}{\Gamma(D_1^{\pm} \rightarrow D^{\mp} \pi^{\pm})}$	2.3 ± 0.6	2.3
$\frac{\Gamma(D_1^0 \rightarrow D^{*+} \pi^-)}{\Gamma(D_1^{\pm} \rightarrow D^{*\mp} \pi^{\pm})}$	$1.9 \pm 1.1 \pm 0.3$	2.3
$\frac{\Gamma(D_1^0)}{\Gamma(D_1^{\pm})}$	0.82 ± 0.5	0.32
$\frac{\Gamma(D_2^0)}{\Gamma(D_2^{\pm})}$	1.12 ± 0.5	0.35

TABLE II. Ratios of partial and total widths for D_1 and D_2 mesons. The numbers in the second column are the experimental ratios, while the numbers in the third column are the leading order HQET predictions.

D_1 and D_2 are constrained by spin-flavor symmetry to decay via D -wave pion emission. The channels which are allowed are

$$D_2 \rightarrow D^* + \pi, \quad (11)$$

$$D_2 \rightarrow D + \pi, \quad (12)$$

$$D_1 \rightarrow D^* + \pi. \quad (13)$$

For these decays, we obtain the well known results of table II [15].

Clearly, ratios of partial widths work very well, while ratios of total widths, which are just the sum of partial widths, only agree at the level of one to two standard deviations. Different interpretations for this discrepancy have been given in the literature. One possibility is to assume that the widths of D_1 could receive a contribution from two pion decay (non-resonant or through an intermediate ρ meson) to the ground state D [16]

$$D_1 \rightarrow D + \pi + \pi, \quad (14)$$

$$D_1 \rightarrow D + \rho \rightarrow D + \pi + \pi. \quad (15)$$

This could broaden the D_1 if there is no analogous enhancement in the D_2 decay and consequently increase the ratio $\frac{\Gamma(D_1)}{\Gamma(D_2)}$ without changing partial ratios. However, up to now, there is no experimental evidence of such an effect.

Another option is to assume a mixing of the narrow D_1 with the broad D_1' ($J_P^P = \frac{1}{2}^+$) [15]. Since D_1' decays via S -wave pion emission rather than D -wave, it is expected to be much broader. Mixing of states is forbidden by the spin symmetry but is allowed when $1/m_Q$ effects are included. However, so far, there is no evidence of an S -wave component in the decay of $D_1 \rightarrow D^* + \pi$ [17]. Another explanation, fully consistent with the HQET, has been given by Falk and Mehen [7]. They argue that the discrepancy of total width ratios could be due to terms of subleading order in the $1/m_Q$ expansion. They found that the experimental ratio $\frac{\Gamma(D_1)}{\Gamma(D_2)}$ can be predicted without involving mixing of states, (even though they studied the possibility of such mixing). These corrections from subleading order in the heavy quark expansion are beyond the scope of this manuscript and are left for a possible future work.

J^P	J^P	State	Mass (MeV)	Γ (MeV)	Γ_{B^*} (MeV)	Γ_{B^*} (MeV)
$\frac{1}{2}^+$	0^-	B^-	5279.2 ± 1.8	$\tau = 1.56 \pm 0.04$ ps	—	—
		B^\pm	5278.9 ± 1.5	$\tau = 1.65 \pm 0.04$ ps	—	—
	1^-	B^*	5324.8 ± 1.8	< 6	no data	—
$\frac{3}{2}^+$	1^+	B_1	~ 5700	20 ± 7	no data	no data
	2^+	B_2	~ 5700	25 ± 7	no data	no data
$?$	$?$	B_f	5698 ± 12	128 ± 18	seen	seen

TABLE III. Summary of B meson experimental status. J_l^P is the spin-parity of the light degrees of freedom according to the HQET.

Ratios of widths	$m_{B_1} = m_{B_2} = 5.68$	$m_{B_1} = 5.725, m_{B_2} = 5.737$	$m_{B_1} = 5.780, m_{B_2} = 5.794$	Experiment
$\Gamma(B_1 \rightarrow B^* + \pi) / \Gamma(B_2 \rightarrow B^* + \pi)$	1.30	1.17	1.08	no data
$\Gamma(B_1 \rightarrow B^* + \pi) / \Gamma(B_2 \rightarrow B^* + \pi)$	0.60	0.71	0.70	no data
$\Gamma(B_1 \rightarrow B^* + \pi) / \Gamma(B_2 \rightarrow B^* + \pi)$	0.78	0.82	0.75	no data
$\Gamma(B_1 \rightarrow B^* + \pi) / \Gamma(B_2 \rightarrow B^* + \pi)$	1.38	1.53	1.45	1.25 ± 7

TABLE IV. Ratios of partial and total widths for B_1 and B_2 . The numbers in the columns two and three are the leading order predictions of HQET using experimental masses found in the literature while the numbers in column four are predictions using masses obtained via relations between B mesons and D mesons. The numbers in the last column are the experimental values.

B. B_1 and B_2

Because of the flavor-symmetry, ratios of decay rates calculated for D_1 and D_2 are also valid for B_1 and B_2 as long as we use the correct masses and pion momenta. Moreover, since $\Lambda_{QCD}/m_b \simeq 0.1$, $1/m_b$ corrections to the leading order should be, in this case, much smaller than for the D mesons ($\Lambda_{QCD}/m_c \simeq 0.3$).

Unfortunately, B mesons are not very well known experimentally. A short summary of the experimental status of bottom mesons is given in table III. The masses of the B_1 and B_2 are not precisely known, and only a few decay rates are available in the literature. Consequently, since our predictions of widths are extremely sensitive to the masses of B_1 and B_2 , we present different ratios using different masses found in the literature.

Ratios of partial and total widths for B_1 and B_2 are given in table IV. The first two columns are HQET predictions using experimental masses from [10–13]. The third column contains HQET predictions using masses obtained by applying the spin-flavor symmetry of HQET. This symmetry relates m_{B_1} and m_{B_2} to m_{D_1} and m_{D_2} , which are precisely known [7]. More precisely, this symmetry relates $m_{B_1} - m_{B_2}$ to $m_{D_1} - m_{D_2}$, as well as $m_{D_1} - m_{D_2}$ to $m_{B_1} - m_{B_2}$, modulo $1/m_Q$ corrections. One therefore expects that the theoretical estimates of the masses should be accurate up to $1/m_Q$ corrections. Finally the last column gives experimental results. At present, there are no experimental errors for the widths, thus the only experimentally determined ratio must be interpreted with some caution.

From our D meson results, one might expect more reliable ratios of partial widths than total widths. In addition, since $\Lambda_{QCD}/m_b \simeq 0.1$, $1/m_b$ corrections should be much smaller than for the D mesons, and predictions more reliable. However, due to the uncertainties of the masses we cannot really take advantage of the expected better convergence of the $1/m_Q$ expansion. As a result we can not make any clear prediction, as we note that our results are extremely mass dependent but are in reasonable agreement with the only experimental data available.

We can also attempt to predict absolute partial as well as absolute total widths for B_1 and B_2 using D mesons decay rates. Let us denote the pion momenta in the processes $B_2 \rightarrow B^* \pi$, $B_2 \rightarrow B \pi$ and $B_1 \rightarrow B^* \pi$ as \vec{p}_{2B^*} , \vec{p}_{2B} and \vec{p}_{1B} , respectively (with a similar notation for the corresponding D decays). Then the partial widths of B_1 and B_2 are related to those of the D_2 by

$$\frac{\Gamma(B_2 \rightarrow B^* + \pi)}{\Gamma(D_2)} = \frac{m_{D_2}}{m_{B_2}} \frac{3/5 |\vec{p}_{2B^*}|^6 m_{B^*}}{6/15 |\vec{p}_{2D}|^6 m_D + 3/5 |\vec{p}_{2D^*}|^6 m_{D^*}}, \quad (16)$$

Widths (MeV)	$m_{B_1} = m_{B_2} = 5.68$	$m_{B_1} = 5.725, m_{B_2} = 5.737$	$m_{B_1} = 5.780, m_{B_2} = 5.794$	Experiment
$\Gamma(B_2 \rightarrow B^* + \pi)$	4 ± 1	8 ± 2	16 ± 5	no data
$\Gamma(B_2 \rightarrow B^* + \pi)$	3 ± 1	7 ± 2	14 ± 4	no data
$\Gamma(B_2)$	7 ± 2	16 ± 4	29 ± 9	25 ± 7
$\Gamma(B_1 \rightarrow B^* + \pi)$	0	0	0	no data
$\Gamma(B_1 \rightarrow B^* + \pi)$	5 ± 2	10 ± 3	20 ± 6	no data
$\Gamma(B_1)$	5 ± 2	10 ± 3	20 ± 6	20 ± 7

TABLE V. Widths of B_1 and B_2 mesons. The numbers in the two first columns contain leading order predictions of HQET using experimental masses while the numbers in the third column present predictions using masses obtained via relations between B mesons and D mesons. The last column shows experimental data.

$$\frac{\Gamma(B_2 \rightarrow B^* + \pi)}{\Gamma(D_2)} = \frac{m_{D_2}}{m_{B_2}} \frac{6/15 |\vec{p}_{2B^*}|^6 m_{B^*}}{6/15 |\vec{p}_{2D}|^6 m_D + 3/5 |\vec{p}_{2D^*}|^6 m_{D^*}}, \quad (17)$$

$$\frac{\Gamma(B_1 \rightarrow B^* + \pi)}{\Gamma(D_2)} = \frac{m_{D_2}}{m_{B_1}} \frac{|\vec{p}_{1B^*}|^6 m_{B^*}}{6/15 |\vec{p}_{2D}|^6 m_D + 3/5 |\vec{p}_{2D^*}|^6 m_{D^*}}. \quad (18)$$

It would have been simpler to simply use the equations for the ratios of partial widths, but the branching ratios for $D_2 \rightarrow D^{(*)} \pi$ and $D_1 \rightarrow D^* \pi$ have not yet been determined. We remind the reader that equations (16), (17) and (18) are strictly leading order predictions of HQET. We have not included any $1/m_Q$ effects. This means that B_1 and B_2 as well as D_1 and D_2 decay only via D -wave pion emission.

Decay rates of B_1 and B_2 predicted by equations (16), (17) and (18) are shown in table V. The theoretical errors are obtained using experimental uncertainties for D meson widths. Here again, the first two columns are leading order predictions of HQET using experimental masses while the third column shows predictions using masses obtained via relations between B mesons and D mesons. The last column contains experimental results.

The decay rates of the two first columns (the ones using experimental masses) are somewhat lower than the experimental values. On the other hand the third column, the one using the spin-flavor symmetry for the masses, is in good agreement with the experimental results. At this stage we do not make any definite conclusions since the experimental data are not sufficiently precise. However it will be interesting to follow the evolution of the experimental masses of B_1 and B_2 to see if they get closer to what we expect from the heavy quark symmetry or not.

C. Strange mesons

Using the heavy quark limit for B and D mesons is a reasonable approximation, but one might also ask how well can the strange quark be described in this limit. In order to partially answer that question, we apply the heavy quark limit to kaons. Doing this allows us to test the heavy quark predictions in more excited states than previously. Nevertheless one has to keep in mind that, in the following results, we consider the s quark as heavy, which is far less reasonable than for the b or c quark. This has been done with some success by Mannel [8], for example.

In order to apply HQET to strange mesons we first need to identify heavy meson doublets for excited kaons. We do this in the following manner. First we retain states with data available for pion emission, namely $K^{**} \rightarrow K^{(*)} + \pi$. Then, we search for two states which have a good set of spin-parity (for example $(0^-, 1^-)$ or $(1^+, 2^+)$) with about 100 – 150 MeV mass splitting. This splitting, which arises from subleading order in heavy quark expansions, is expected to be not more than 200 MeV, as quark models indicate [18]. Once such a pair of states is found, we identify them as possible members of a doublet. We then compare their experimental and theoretical ratios of decay rates for pion emission. If they are similar, then perhaps we have made a believable identification of a doublet.

1. Positive parity kaons.

The status of positive parity kaon resonances is summarized in table VI. From these nine resonances we found four states as possible members of two doublets.

The pair $(K_1(1270), K_2(1430))$ could be the lowest lying $(1^+, 2^+)$ doublet ($J^P = \frac{3}{2}^+$). The comparison between experimental ratios of widths and the HQET predictions are shown in table VII. The second column of this table

J^P	State	Mass (MeV)	Γ (MeV)	Γ_{K^*} (MeV)	Γ_{K^*+} (MeV)
1^+	$K_1(1270)$	1273 ± 7	90 ± 20	no data	14.5 ± 5.5
1^+	$K_1(1400)$	1402 ± 7	195 ± 25	no data	183 ± 26
0^+	$K_0(1430)$	1429 ± 9	$287 \pm 10 \pm 21$	270 ± 40	no data
2^+	$K_2^*(1430)$	1425.6 ± 1.3	98.5 ± 2.7	52 ± 5	26.5 ± 3
1^+	$K_1(1650)$	1650 ± 50	150 ± 50	no data	no data
0^+	$K_0^*(1950)$	1945 ± 30	$201 \pm 34 \pm 79$	104 ± 71	no data
2^+	$K_2^*(1980)$	1975 ± 33	$373 \pm 33 \pm 60$	seen	no data
4^+	$K_4^*(2045)$	2045 ± 9	198 ± 30	20 ± 4	no data
3^+	$K_3(2320)$	2324 ± 24	150 ± 30	no data	no data

TABLE VI. Experimental status of positive parity kaon resonances.

Ratio of widths	Experiment	Heavy quark prediction
$\Gamma(K_1(1270) \rightarrow K^* \pi) / \Gamma(K_1(1270) \rightarrow K^* \pi)$	0.55 ± 0.45	0.36
$\Gamma(K_1(1400) \rightarrow K^* \pi) / \Gamma(K_1(1400) \rightarrow K^* \pi)$	0.3 ± 0.4	0.35
$\Gamma(K_2^*(1430) \rightarrow K^* \pi) / \Gamma(K_2^*(1430) \rightarrow K^* \pi)$	0.51 ± 0.04	0.99
$\Gamma(K_0(1430) \rightarrow K^* \pi) / \Gamma(K_0(1430) \rightarrow K^* \pi)$	1.45 ± 0.50	0.80

TABLE VII. Ratios of widths for the $(1^+, 2^+)$ doublet ($K_1(1270), K_2(1430)$), and for the $(0^+, 1^+)$ doublet ($K_0(1430), K_1(1400)$). The second column shows the experimental data while the third column shows the leading order HQET predictions.

shows the experimental ratios while the third column shows the HQET predictions. Experimental uncertainties on these ratios are of the order of 100% except for the last ratio. The HQET predictions are in good agreement with experimental ratios for the first two cases. On the last ratio, however, our prediction is too high by a factor of two. In this specific case it would be particularly interesting to calculate $1/m_Q$ corrections (including mixing effects) and see if they can decrease the ratio to something closer to the experimental one.

The pair ($K_0^*(1430), K_1(1400)$) could be the lowest lying $(0^+, 1^+)$ doublet ($J_P^P = \frac{1}{2}^+$). The comparison between experimental ratios of widths and the HQET predictions are shown in table VII. In this case, the experimental uncertainty on the ratio of rates is smaller than the previous pair of states. However the width of $K_1(1400)$ is not very well known (i.e. different experiments give quite different widths). We chose to use the width given by Daum *et al.* [19] ($\Gamma(K_1(1400)) = 195 \pm 25$ MeV) and not the widths from [9] because the branching ratio is extracted from this experiment. This gives us a partial width of $\Gamma(K_1(1400) \rightarrow K^* + \pi) = 183 \pm 26$ MeV. The HQET prediction is lower than the experimental ratio. However, since one expects $1/m_Q$ corrections to be important in the case of the s quark, we believe that the previous identification is reasonable. On the other hand, the identification is based on only one ratio. Therefore in this particular case more data are crucial in order to validate the doublet.

We comment here on the choice of the $K_1(1270)$ as the member of this multiplet, instead of the $K_1(1400)$. The HQET prediction is that the two members of a multiplet will have the same total width, if they are degenerate. Breaking this degeneracy would yield slightly different widths. Since the K_2 has a total width of 98.5 MeV, and the state at 1270 has a total width of 90 MeV, we thought that this was a closer match than a total width of 195 MeV. In addition, the widths for the pion-emission decays of these states also give some clue as to how they should be assigned.

A better test would be the partial waves in the pion decays of these states, as the members of the $(1^+, 2^+)$ doublet should decay only through D-wave pion emission. In the absence of such information, the only criterion is the total width, which leads us to pair the states as we have. In addition, we can examine the comparison between the HQET prediction and experiment if we switch the assignments of the two 1^+ states. This comparison is shown in table VIII. As can be seen, the ratios obtained with this switch are in complete disagreement with the HQET predictions. Finally, we note Isgur [20] has placed these states in the same doublets that we have.

It may appear discouraging that only two possible doublets were found since nine positive parity kaons are experimentally known. The reason is that only six states have experimentally measured pion emission decay rates, and only four states out of nine could be tested as members of a doublet. We believe that it is quite encouraging to be able to

Ratio of widths	Experiment	Heavy quark prediction
$\Gamma(K_1(1400) \rightarrow K^* \pi) / \Gamma(K_1(1400) \rightarrow K^* \pi)$	6.9 ± 0.8	1.46
$\Gamma(K_2^*(1430) \rightarrow K^* \pi) / \Gamma(K_2^*(1430) \rightarrow K^* \pi)$	3.5 ± 0.4	1.38
$\Gamma(K_0(1430) \rightarrow K^* \pi) / \Gamma(K_0(1430) \rightarrow K^* \pi)$	0.51 ± 0.04	0.99
$\Gamma(K_1(1270) \rightarrow K^* \pi) / \Gamma(K_1(1270) \rightarrow K^* \pi)$	18.7 ± 7.0	1.46

TABLE VIII. Ratios of widths for the $(1^+, 2^+)$ doublet ($K_1(1400), K_2(1430)$), and for the $(0^+, 1^+)$ doublet ($K_0(1430), K_1(1270)$). The second column shows the experimental data while the third column shows the leading order HQET predictions. The assignments of the two 1^+ states are switched from table VII.

J^P	State	Mass (MeV)	Γ (MeV)	Γ_{K^*} (MeV)	Γ_{K^*+} (MeV)
0^-	K^*	493.477 ± 0.013	—	—	—
0^-	K^0	497.673 ± 0.031	—	—	—
1^-	$K^{*+}(892)$	891.66 ± 0.26	50.8 ± 0.9	100%	—
1^-	$K^{*0}(892)$	896.1 ± 0.28	50.5 ± 0.8	100%	—
1^-	$K^*(1410)$	1414 ± 15	232 ± 21	15 ± 3	$> 93 \pm 9$
0^-	$K(1460)$	~ 1460	~ 260	no data	~ 109
2^-	$K_2^*(1580)$	~ 1580	~ 110	no data	seen
1^-	$K^*(1680)$	1717 ± 27	322 ± 110	124 ± 43	98 ± 35
2^-	$K_2^*(1770)$	1773 ± 8	198 ± 14	no data	seen
3^-	$K_3^*(1780)$	1776 ± 7	169 ± 21	29 ± 4	32 ± 9
2^-	$K_2^*(1820)$	1816 ± 13	278 ± 35	no data	seen
0^-	$K(1830)$	1830 ± 3	250	no data	no data
2^-	$K_2^*(2250)$	2247 ± 17	180 ± 30	no data	no data
5^-	$K_5^*(2380)$	$2382 \pm 14 \pm 19$	$178 \pm 37 \pm 32$	11 ± 5	no data
4^-	$K_4(2500)$	2490 ± 20	250	no data	no data

TABLE IX. Experimental status of negative parity kaon resonances.

find two possible doublets (i.e. four states) with only four states tested.

2. Negative parity kaons

The experimental status of the known negative parity kaon resonances is summarized in table IX. Including K and K^* , thirteen negative parity resonances are experimentally known. Unfortunately, data for pion emission are available for only four of these states. Consequently, we are unable to clearly identify any doublets. However, we are still able to ratios of decay widths for two states. However in each case, the multiplet partner has to be found.

$K^*(1680)$ could be the 1^- state of a $(1^-, 2^-)$ doublet ($J_P^P = \frac{3}{2}^-$). The comparison between experimental ratios of widths and the HQET predictions can be found in table X. The second column shows the experimental ratio, while the third column shows the HQET prediction, which is in very good agreement with the experimental ratio. If, instead, we identify this state as the 1^- state of a $(0^-, 1^-)$ doublet, with ($J_P^P = \frac{1}{2}^-$), the HQET prediction for the ratio of partial widths is 0.20. This is far from the experimental value. In these two scenarios, the possible multiplet partners are the $K(1460)$ or the $K_2(1580)$. In either case, the partial width for pion emission has not been measured.

$K_3^*(1780)$ could be identified with the 3^- state of a $(2^-, 3^-)$ doublet ($J_P^P = \frac{5}{2}^-$). The comparison between experimental ratios of widths and the HQET predictions are also shown in table X. Here again, the HQET prediction is very close to the experimental ratio.

For comparison, if we take this state as the 3^- state of a $(3^-, 4^-)$ doublet ($J_P^P = \frac{7}{2}^-$) instead of a $(2^-, 3^-)$ doublet ($J_P^P = \frac{5}{2}^-$), the HQET prediction for the ratio of partial widths is 0.5, which is more than two times smaller than the experimental value.

There are two possible partners for $K_3^*(1780)$, namely $K_2(1770)$ and $K_2(1820)$. Both of them are in the expected mass range but data for pion emission exist for neither.

Ratio of widths	Experiment	Heavy quark prediction
$\Gamma(K^*(1680) \rightarrow K^* \pi) / \Gamma(K^*(1680) \rightarrow K^* \pi^*)$	$1.3^{+0.75}_{-0.14}$	1.3
$\Gamma(K^*(1780) \rightarrow K^* \pi) / \Gamma(K^*(1780) \rightarrow K^* \pi^*)$	1.09 ± 0.20	1.4

TABLE X. Ratio of widths for $K^*(1680)$ in a $(1^-, 2^-)$ doublet, and for $K^*(1780)$ in a $(2^-, 3^-)$ doublet. The numbers in the second column are the experimental ratios, while the numbers in the third column are the HQET predictions.

Decay	Experiment (MeV)	Heavy quark prediction (MeV)
$K_1(1270) \rightarrow K^* \pi$	14 ± 6	12
$K_2(1430) \rightarrow K \pi$	49 ± 3	33
$K_2(1430) \rightarrow K^* \pi$	24 ± 2	33
$D_1 \rightarrow D^* \pi$	21 ± 4	13
$D_2 \rightarrow D^* \pi + D_2 \rightarrow D \pi$	24 ± 4	38

TABLE XI. Decay widths for states in the $(1^+, 2^+)$ doublet, assuming that the spin-flavor symmetry holds. The second column shows the experimental values, while the third column shows the HQET predictions.

For negative parity kaons, although we could only compare with two experimental ratios, we believe that the evidence supports our assignment of states to multiplets. First, our predictions are in good agreement with the experimental ratios. Second, one can find reasonable partners for $K^*(1780)$. Unfortunately, so far, there are no data available for pion emission for these partners.

D. Spin-flavor symmetry

1. Spin-flavor symmetry for the $(1^+, 2^+)$ doublets

The spin-flavor symmetry tells us that the decay rate of a state from a $(1^+, 2^+)$ doublet to a state from a $(0^-, 1^-)$ doublet is described in terms of a single coupling constant, independent of the flavor of the heavy quark. This means that the coupling constant describing the processes

$$(K_1, K_2) \rightarrow (K, K^*) + \pi, \quad (19)$$

$$(D_1, D_2) \rightarrow (D, D^*) + \pi, \quad (20)$$

$$(B_1, B_2) \rightarrow (B, B^*) + \pi, \quad (21)$$

is the same. We can test the extent to which this symmetry holds by examining the coupling constants for the decays mentioned.

At leading order in HQET, the width of any process $A \rightarrow B + \pi$ is given by

$$\Gamma_i = |\alpha|^2 f_i(m_A, m_B, m_C, p_\pi^2) \quad (22)$$

where f_i is a known function given by the tensor formalism and phase space. Thus, if the spin-flavor symmetry is valid, the ratio $\Gamma_i/f_i(m_A, m_B, m_C, p_\pi^2)$ should be the same for all the processes. Alternatively, we should be able to fit all of these processes using a single value of α .

The results of such a fit are shown in table XI. In obtaining this fit, we have averaged the decay rates of the different charge states of the excited D mesons. We note that for the D mesons, we already mentioned the discrepancy between the ratio of total decay rates of the D_1 and D_2 mesons, and the value predicted from HQET. While these results clearly point to the need for $1/m_Q$ corrections, they are nevertheless somewhat encouraging.

If we use the value of the constant α obtained from this fit, and apply it to the corresponding B meson decays, the results we obtain are shown in table XII. These results are to be compared with those of table V. All the widths in table XII are bigger than the corresponding ones in table V by about 50%. The numbers in the second column are still low, but now the numbers in the fourth column, which were in agreement with experimental data, are too high. The numbers in the third column are now in agreement (within the error bars) with the data.

Widths (MeV)	$m_{B_1} = m_{B_2} = 5.68$	$m_{B_1} = 5.725, m_{B_2} = 5.737$	$m_{B_1} = 5.780, m_{B_2} = 5.794$	Experiment
$\Gamma(B_2 \rightarrow B + \pi)$	6 ± 1.5	12 ± 3	22 ± 8	no data
$\Gamma(B_2 \rightarrow B^* + \pi)$	4.5 ± 1.5	10.5 ± 3	21 ± 6	no data
$\Gamma(B_2)$	10.5 ± 3	22 ± 6	44 ± 12	25 ± 7
$\Gamma(B_1 \rightarrow B + \pi)$	0	0	0	no data
$\Gamma(B_1 \rightarrow B^* + \pi)$	7.5 ± 3	15 ± 4.5	30 ± 9	no data
$\Gamma(B_1)$	7.5 ± 3	15 ± 4.5	30 ± 9	20 ± 7

TABLE XII. Widths of B_1 and B_2 mesons using the "average" coupling constant obtained from fitting to the corresponding D and K meson widths. The numbers of the two first columns are leading order predictions of HQET using experimental masses while the numbers of the third column show predictions using masses obtained via relations between B mesons and D mesons. The last column shows experimental data.

2. Spin-flavor symmetry for $(0^+, 1^+)$ doublets

After the encouraging results of table XI (i.e. applying HQET to the strange quark), we can try to glean some information about the widths of the charm and the bottom lowest lying $(0^+, 1^+)$ doublet using the strange doublet $(0^+, 1^+)$. The charm and beauty $(0^+, 1^+)$ doublets have not yet been experimentally found, mainly because these states are expected to be broad. In what follows, we use masses obtained using a quark model [26]. The quark model masses for these states are respectively $m_{D_0} = 2270$ MeV, $m_{D_1} = 2400$ MeV, $m_{B_0} = 5.65$ GeV and $m_{B_1} = 5.69$ GeV.

Using experimental decay rates associated with the strange $(0^+, 1^+)$ doublet ($K_0^*(1430)$, $K_1(1400)$), we can predict the widths for the corresponding charm and beauty $(0^+, 1^+)$ doublets. These are shown in table XIII.

The HQET predictions, decay rates around 70 MeV, are somewhat smaller than one expects from most quark models. The model of Goity and Roberts [27] predicts widths of about 120 MeV, while most other models predict much larger widths [28]. The differences between the two sets of quark model predictions have been attributed to relativistic effects [27]. What is significant, we believe, is that the HQET predictions are of similar size to those predicted by reference [27]. Nevertheless, there are a number of possibilities for generating larger widths using HQET.

The HQET predictions are quite sensitive to the masses, and if we increase the masses of D_0 , D_1 and B_0 , B_1 by 100 MeV one finds widths of the order of 120 MeV for D_0 and D_1 and 140 MeV for B_0 and B_1 , very much in agreement with the work of Goity and Roberts [27]. Perhaps here we have a hint that the quark model predicted masses of D_0 , D_1 and B_0 , B_1 are too low. Another possibility is that our identification of ($K_0^*(1430)$, $K_1(1400)$) as the lowest lying $(0^+, 1^+)$ doublet is incorrect. This would make it meaningless to extrapolate the coupling constant to the corresponding charm and beauty mesons. Finally, one can assume that the doublet identification is correct but that $1/m_Q$ corrections are very important (especially for the strange $(0^+, 1^+)$ doublet ($K_0^*(1430)$, $K_1(1400)$), and that if we included these corrections, we could predict larger widths.

Widths (MeV)	$m_{D_0} = 2.27, m_{D_1} = 2.40$ GeV	$m_{D_0} = 2.37, m_{D_1} = 2.50$ GeV
$\Gamma(D_0 \rightarrow D + \pi)$	70 ± 5	120 ± 10
$\Gamma(D_1 \rightarrow D^* + \pi)$	67 ± 5	120 ± 10
Widths (MeV)	$m_{B_0} = 5.65, m_{B_1} = 5.69$ GeV	$m_{B_0} = 5.75, m_{B_1} = 5.79$ GeV
$\Gamma(B_0 \rightarrow B + \pi)$	70 ± 5	140 ± 12
$\Gamma(B_1 \rightarrow B^* + \pi)$	67 ± 5	140 ± 12

TABLE XIII. Predictions of the decay rates of the lowest lying $(0^+, 1^+)$ charm and bottom doublets using spin-flavor symmetry.

IV. CONCLUSION

In the previous sections, we have used the heavy quark tensor formalism to analyze strong decays of excited heavy hadrons. We have compared experimental and theoretical ratios of decay rates for B meson, D meson and kaons. We have not compared our predictions with data in the baryon sector, as baryon data are either not yet sufficiently

precise, or not yet measured, for such comparison to be meaningfully made. Our results are in agreement with the spin-counting methods of Isgur and Wise. We have found some encouraging results if we treat the strange quark as heavy. Nevertheless, in this case, one would certainly expect $1/m_Q$ corrections to be very important. For such reasons we believe that terms of subleading order in the heavy quark expansion should be studied. In addition, the experimental situation in all sectors needs to be improved before we can make more precise tests of the predictions of HQET. In the strange sector, experiments that will be carried out at the Brookhaven National Laboratory, and perhaps also at Jefferson Laboratory, should help remedy this situation.

ACKNOWLEDGEMENT

The support of the National Science Foundation through grant 947582, and of the Department of Energy through grants DE-FG05-94ER40832 and DE-AC05-84ER40150 is gratefully acknowledged.

-
- [1] W. Roberts, Phys. Rev. D **58** (1998) 034007.
 - [2] See for example M. Neubert, Phys. Rep. C **245** (1994) 259, and references therein.
 - [3] H. Georgi, Phys. Lett. B **240** (1990) 447.
 - [4] N. Isgur and M. Wise, Phys. Lett. B **232** (1989) 113; Phys. Lett. B **237** (1990) 527; B. Grinstein, Nucl. Phys. B **339** (1990) 253; A. Falk, H. Georgi, B. Grinstein and M. Wise, Nucl. Phys. B **343** (1990) 1; A. Falk and B. Grinstein, Phys. Lett. B **247** (1990) 406; T. Mannel, W. Roberts and Z. Ryzak, Nucl. Phys. B **368** (1992) 204.
 - [5] N. Isgur and M. Wise, Phys. Rev. Lett. **66** (1991) 1130.
 - [6] J. L. Goity and W. Roberts, Phys. Rev. D **51** (1995) 3459.
 - [7] A. Falk and T. Mehen, Phys. Rev. D **53** (1996) 231.
 - [8] A. Ali, T. Mannel and T. Ohl, Phys. Lett. B **298** (1993) 195.
 - [9] Review of Particle Physics, The European Physics Journal C **4** (1998).
 - [10] S. Godfrey, Invited plenary talk at the 7th International Conference on Hadron Spectroscopy, Brookhaven National Laboratory, August 25-30, 1997.
 - [11] R. Akers *et al.* (OPAL Collaboration), Z. Phys. C **66**, (1995) 19.
 - [12] P. Abreu *et al.* (DELPHI Collaboration), Phys. Lett. B **345**, (1995) 598.
 - [13] D. Buskulic *et al.* (ALEPH Collaboration), Z. Phys. C **89**, (1996) 393.
 - [14] A. Falk, Nucl. Phys. B **378** (1992) 79.
 - [15] M. Lu, M. Wise and N. Isgur, Phys. Rev. D **45** (1992) 1553.
 - [16] A. Falk and M. Luke, Phys. Lett. B **292** (1992) 119; E. Eichten, C. Hill and C. Quigg, Phys. Rev. Lett. **71** (1993) 4116.
 - [17] P. Avery *et al.* (CLEO Collaboration), Phys. Lett. B **331**, (1994) 236; T. Bergfeld *et al.* (CLEO Collaboration), Phys. Lett. B **340**, (1994) 194; Y. Kubota *et al.* (CLEO Collaboration), Phys. Rev. Lett. **72**, (1994) 1972; J. Alexander *et al.* (CLEO Collaboration), Phys. Lett. B **303**, (1993) 377.
 - [18] S. Godfrey and N. Isgur, Phys. Rev. D **32** (1985) 189.
 - [19] C. Daum *et al.*, Nucl. Phys. B **187** (1981) 1.
 - [20] N. Isgur, Phys. Rev. D **57** (1998) 4041.
 - [21] N. Isgur and M. Wise, Nucl. Phys. B **348** (1991) 276; H. Georgi, Nucl. Phys. B **348** (1991) 293; T. Mannel, W. Roberts and Z. Ryzak, Nucl. Phys. B **355** (1991) 38.
 - [22] M. Luke, Phys. Lett. B **252** (1990) 447; H. Georgi, B. Grinstein and M. Wise, Phys. Lett. B **252** (1990) 456; C. G. Boyd and D. E. Brahm, Phys. Lett. B **254** (1991) 468; A. Falk, B. Grinstein and M. Luke, Nucl. Phys. B **357** (1991) 185.
 - [23] J. M. Flynn and N. Isgur, J. Phys. G **18** (1992) 1627.
 - [24] H. Georgi, lectures presented at the Theoretical Advanced Study Institute (TASI), 1991.
 - [25] A. Falk and M. Peskin, Phys. Rev. D **49** (1994) 3320.
 - [26] J. Zeng, J. W. Van Orden and W. Roberts, Phys. Rev. D **52** (1995) 189.
 - [27] W. Roberts and J. L. Goity, Phys. Rev. D **60** (1999) 034001.
 - [28] S. Godfrey and R. Kokoski, Phys. Rev. D **43** (1991) 1679; R. Kokoski and N. Isgur, Phys. Rev. D **35** (1987) 907.
 - [29] S. Capstick and N. Isgur, Phys. Rev. D **34** (1986) 2809.